SCREENING CORRECTIONS IN PHOTO AND DIS PRODUCTION OF J/Ψ

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Abstract

Photo and DIS production of J/Ψ are investigated and compared with calculations based on pQCD in the LLA approximation without and with screening corrections. The calculation includes corrections induced by the real part of the production amplitude, the skewed (off diagonal) gluon distribution function and the relativistic Fermi motion within the charmonium system. Our pQCD results are also compared with the predictions obtained from a Regge type two Pomeron model. Our results show that the screened pQCD model gives a better reproduction of the data than the non screened model. However, the available data does not enable us to exclude any of the three models we have examined. The predictions of these models, when extrapolated to both low and very high energies may provide a more effective discrimination between the different parameterizations.

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1 Introduction

The measurement of high energy photo and deep inelastic scattering (DIS) exclusive production of J/Ψ serves as an important testing ground for checking the validity of pQCD in the limit of a relatively small hardness and small x. The hardness of this process is fixed by $m_c^2 \simeq \frac{1}{4} M_{J/\Psi}^2$, consequently[1][2][3] it is a suitable means of investigating the applicability and possible need for a re-formulation of hard pQCD when approaching the kinematic interface with the less understood npQCD soft domain. Indeed, over the past few years we have been witness to vigorous experimental, phenomenological and theoretical investigations of this process, which supplement the detailed analysis of $F_2(x, Q^2)$, the proton structure function, and its logarithmic derivatives in the small Q^2 and small x limits.

In the following we present a detailed study of J/Ψ photo and DIS exclusive production. Being relatively well measured, it may help to check the self consistency of, and discriminate between, relevant theoretical models . We recall that a key ingredient for determining the parton distribution functions (pdf) is the pQCD analysis of inclusive DIS which utilizes the DGLAP evolution equations[4]. These pdfs are then used as input for the pQCD calculation of exclusive DIS channels (such as J/Ψ production), which are usually executed in the color dipole approximation[5]. We shall mainly be interested in the correlated problems of determining the gluon saturation scale, the role of screening corrections (SC) and the relative importance of the soft npQCD component at the kinematic edge where the hard pQCD is applicable.

As we shall specify in the next section, a realistic calculation of J/Ψ photo and DIS production depends on a few corrections to the original pQCD estimate:

1) K_R^2 accounting for the real part of the production amplitude[6]. The pQCD calculation of Eq. (1) below relates to the imaginary part only.

2) K_G^2 denoting the correction resulting from the contributions of the off diagonal (skewed) gluon distributions[7].

3) K_F^2 denoting the correction due to Fermi motion of the heavy quark within the quarkonium system[8]. As such, it accounts for the deviations from the simple static non relativistic estimate of the vector meson wave function.

These corrections contribute significantly to the final (amplitude squared) estimate. Thus, in our investigation we shall assess possible ambiguities in our calculations which may be associated with the estimated corrections to the bare pQCD calculation. Our analysis follows the same lines as those of our recent paper[9] on $\partial F_2/\partial \ln Q^2$.

2 Photo and DIS production of J/Ψ

The procedure for calculating the forward differential cross section for photo and DIS production of a heavy vector meson in the color dipole approximation is straightforward. The calculation is performed[1][2][3][10][11] in the LLA, assuming the produced vector meson quarkonium system to be non relativistic. The contribution of pQCD to the imaginary part of the $t = 0$ differential cross section of photo and DIS production of heavy vector mesons is given by

$$\left(\frac{d\sigma(\gamma^* p \rightarrow Vp)}{dt}\right)_{t=0}^{pQCD} = \frac{\pi^3 \Gamma_{ee} M_V^3}{48\alpha} \frac{\alpha_S^2(\bar{Q}^2)}{\bar{Q}^8} \left(xG^{DGLAP}(x, \bar{Q}^2)\right)^2 \left(1 + \frac{Q^2}{M_V^2}\right), \quad (1)$$

where, xG^{DGLAP} is the gluon distribution function as obtained from the DGLAP analysis. In the non relativistic limit we have

$$\bar{Q}^2 = \frac{M_V^2+Q^2}{4}, \qquad x = \frac{4\bar{Q}^2}{W^2}. \tag{2}$$

In the following we discuss the photo and DIS production of J/Ψ as there is an abundance of data available in this channel [12][13][14] spanning a relatively wide energy range. From a theoretical point of view, its hardness is comparable to those we have investigated in our $\partial F_2/\partial \ln Q^2$ analysis[9]. In this study we have shown that the recent HERA data on the Q^2 logarithmic slope of F_2 is well reproduced by DGLAP with either the CTEQ5HQ pdf input[15], or by the GRV98NLO input[16] which is corrected for SC[17]. As we wish to maintain the compatibility of the F_2 and the J/Ψ production interpretations, we have confined our pQCD calculations only to the above two pdfs. In order to compare with the experimental data, which are given as integrated cross sections, to Eq. (1), we need to know B - the J/Ψ forward differential cross section slope. The experimental values are approximately constant with a possible moderate energy dependence[12]. Theoretically, each of the models we shall consider has a somewhat different estimate of B which we shall specify.

The main difficulty with a pQCD analysis of J/Ψ is the observation that the simple dipole calculation needs to be corrected for the following reasons:

1) A correction for the contribution of the real part of the production amplitude. This correction is well understood[6] and is given by

$$K_R^2 = (1+\rho^2), \qquad \rho = ReA/ImA = tg(\tfrac{\pi\lambda}{2}), \qquad \lambda = \partial\ln(xG^{DGLAP})/\partial\ln(\tfrac{1}{x}). \tag{3}$$

We note that λ has a mild dependence on x at a fixed $\bar{Q}^2$.

2) A correction for the contribution of the skewed (off diagonal) gluon distributions. This correction is calculated[7] to be

$$K_G^2 = \left(\frac{2^{2\lambda+3}\,\Gamma(\lambda+2.5)}{\sqrt{\pi}\,\Gamma(\lambda+4)}\right)^2. \tag{4}$$

3) A more controversial issue relates to the non relativistic approximation assumed for the J/Ψ charmonium. Relativistic effects, produced by the Fermi motion of the bound quarks, result in a considerable reduction of the calculated pQCD cross section[8]. The correction, K_F^2, is very sensitive to the value of m_c. Ref.[8] assumes that $m_c \simeq 1.50\,GeV$ and obtains $K_F^2 \simeq 0.25$ with almost no energy dependence. However, we note that the calculation of K_F^2, regardless of its detailed construction, is very sensitive to the c-quark mass since a small change in the input value of m_c changes the estimate of K_F^2 significantly. Clearly, if we assume that $m_c = \frac{1}{2}M_{J/\Psi} \simeq 1.55\,GeV$, i.e. a change of only about $50\,MeV$ relative to the value assumed in Ref.[8], the Fermi correcting factor is identical to 1. We will, therefore, consider K_F^2 as a free (energy independent) parameter. As we shall see, a calculation based on CTEQ5 gives $K_F^2 \simeq 1.00$, whereas a calculation based on GRV98 with SC gives $K_F^2 = 0.70$. This value corresponds to a c-quark mass of approximately $1.52\,GeV$.

Based on the above, the expression for the integrated cross section is written

$$\sigma(\gamma^* p \to J/\Psi p) \;=\; K_R^2 \cdot K_G^2 \cdot K_F^2 \cdot \frac{1}{B} \cdot \left(\frac{d\sigma}{dt}\right)^{pQCD}_{t=0} , \qquad (5)$$

where $\left(\frac{d\sigma}{dt}\right)^{pQCD}_{t=0}$ is given by Eq. (1), B (the forward differential slope) is taken from the data and K_F^2 is a free parameter.

We wish to present an analysis for J/Ψ photo and DIS pQCD cross sections which is compatible with our recent investigation[9] of the Q^2 logarithmic slope of F_2. Note that the F_2 DGLAP analysis has been performed in NLO while the present calculation is carried out in the LLA modified by the above corrections. In the F_2 investigation we have shown[9] that the recent logarithmic slope data is well reproduced by three, rather different, formulations:

1) A DGLAP calculation with CTEQ5 pdf input. This calculation has no explicit soft contribution.

2) A DGLAP calculation with GRV98 pdf input modified by SC which are calculated[17] in the DLA. This calculation, as well, has no explicit soft contribution.

3) A Regge type two Pomeron parameterization[18] in which the hard contribution is provided by a hard Pomeron, whereas the soft contribution is presented by a soft Pomeron. The two trajectories are parametrized to be

$$\begin{aligned} \alpha^H(t) \;&=\; 1.44 + \, 0.1t \\ \alpha^S(t) \;&=\; 1.08 + \, 0.25t \end{aligned} \qquad (6)$$

In the following we check and compare the above models with the J/Ψ cross sections. Our data base has 49 photo production points, out of which 35 points are HERA data. We have also studied just the 30 points at the high energy end with $W > 50\,GeV$. The DIS data has 47 data points, all of which come from HERA and have $W > 50$ GeV.

1) Our non screened pQCD calculation, denoted CTEQ5NSC, is based on Eq. (5) with CTEQ5 input for $xG^{DGLAP}(x, \bar{Q}^2)$. Our calculations for photo production, compared with the experimental data, are presented in Fig.1. This calculation has only a hard sector and as such in our calculations we took a fixed $B = 4.73\,GeV^{-2}$[13]. We have adjusted the free parameter K_F^2 so as to fit the data base of the integrated J/Ψ photo production and DIS cross section points. The best fit has no Fermi suppression, i.e. $K_F^2 = 1.00$, and has the following values for the corresponding $\frac{\chi^2}{ndf}$:

a) For the complete data base $\frac{\chi^2}{ndf} = 2.12$.

b) For the photo production data $\frac{\chi^2}{ndf} = 3.03$.

c) For the HERA photo production data $\frac{\chi^2}{ndf} = 1.14$.

d) For high energy photo production $(W > 50\,GeV)$ $\frac{\chi^2}{ndf} = 0.92$.

As seen in Fig.1, CTEQ5NSC overestimates the low energy data. In general, the overall x dependence of CTEQNSC is somewhat softer than the harder x behaviour suggested by the data. We conclude that CTEQ5NSC does not produce a good fit to the complete data base. However, its $\frac{\chi^2}{ndf}$ is considerably improved once we ignore the low energy data.

2) For the SC calculation, done in the DLA, we follow our earlier publications[19] and define the damping factors due to the screening in the quark sector i.e. the percolation of the $c\bar{c}$ through the target. This is given by the following expressions for the longitudinal and transverse damping factors

$$D^2_{qL} \; = \; \left(\frac{E_1(\frac{1}{\kappa_q})e^{\frac{1}{\kappa_q}}}{\kappa_q} \right)^2 \tag{7}$$

and

$$D^2_{qT} \; = \; \left(\frac{1 \, + \, (1 \, - \, \frac{1}{\kappa_q})E_1(\frac{1}{\kappa_q})e^{\frac{1}{\kappa_q}}}{2\kappa_q} \right)^2 , \tag{8}$$

where, for $N_c = 3$, we have

$$\kappa_q \; = \; \frac{2\pi\alpha_S}{3R^2\bar{Q}^2} xG^{DGLAP}(x, \bar{Q}^2). \tag{9}$$

The above expressions are derived[19] assuming that $\gamma << 1$, where γ is the DGLAP anomalous dimension. As a result of this approximation we overestimate the SC in the exceedingly small x limit. However, within the kinematical range of this investigation this excess is small enough to be neglected for $x > 10^{-3}$. The correction for smaller x may be as large as 10%. Actually, the exact calculation makes our results moderately harder and consequently improves our reproduction of the data (see Fig.2). We do not consider this to be important as it will result in a small reduction of our present $\frac{\chi^2}{ndf}$ values, which are excellent as they stand. Our expression for D^2_g, the damping in the gluon sector, is the square of the gluon damping used in Refs.[9][17]. Our final expression for the integrated cross section is

$$\sigma(\gamma^* p \rightarrow J/\Psi p) \; = \; K^2_R \cdot K^2_G \cdot K^2_F \cdot \frac{1}{B(R^2)} \cdot \left(\frac{d\sigma}{dt} \right)^{pQCD}_{t=0} \cdot D^2_q \cdot D^2_g, \tag{10}$$

where D_q denotes the L and T components as appropriate. As in our F_2 study[9][17], for $xG^{DGLAP}(x, \bar{Q}^2)$ we use the GRV98 pdf input.

Our calculations as compared with the data are presented in Figs.2 and 3. with an adjusted value of $K^2_F = 0.70$. We get the following values for the corresponding $\frac{\chi^2}{ndf}$:

a) For the complete data base $\frac{\chi^2}{ndf} = 0.94$.

b) For the photo production data $\frac{\chi^2}{ndf} = 0.91$.

c) For the HERA photo production data $\frac{\chi^2}{ndf} = 0.87$.

d) For high energy photo production ($W > 50\, GeV$) $\frac{\chi^2}{ndf} = 0.58$.

As is visible from Fig.2, the suppression induced by the SC is appreciable even though $\kappa_g < 1$, i.e. below gluon saturation. This is consistent with the general observation[20] that SC, which are the consequence of high gluon density, precede the gluon saturation state. Note that $R^2 = 8.5\, GeV^{-2}$, which is the essential parameter in the SC calculation presented both in Ref.[9] and here, is not a free parameter but is determined directly from the J/Ψ photo production forward slope. In a SC model, such as ours, we expect[21] a weak dependence of B on x. This is demonstrated in Fig.4 together with the relevant HERA data. For a non screened calculation B is fixed at $\frac{1}{2}R^2$.

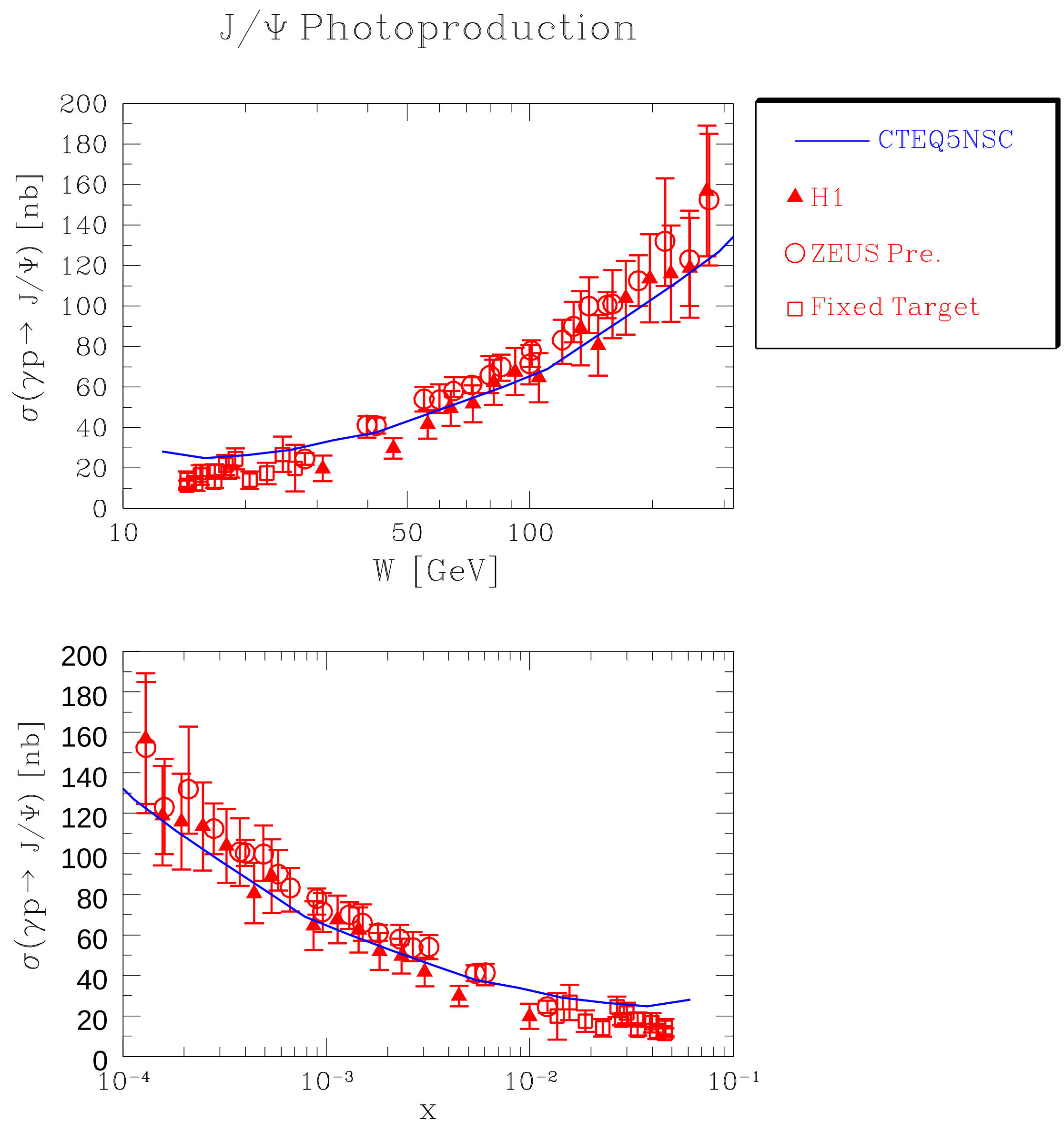

Figure 1: *Photo production of J/Ψ as a function of W and x. Data and CTEQ5NSC calculations.*

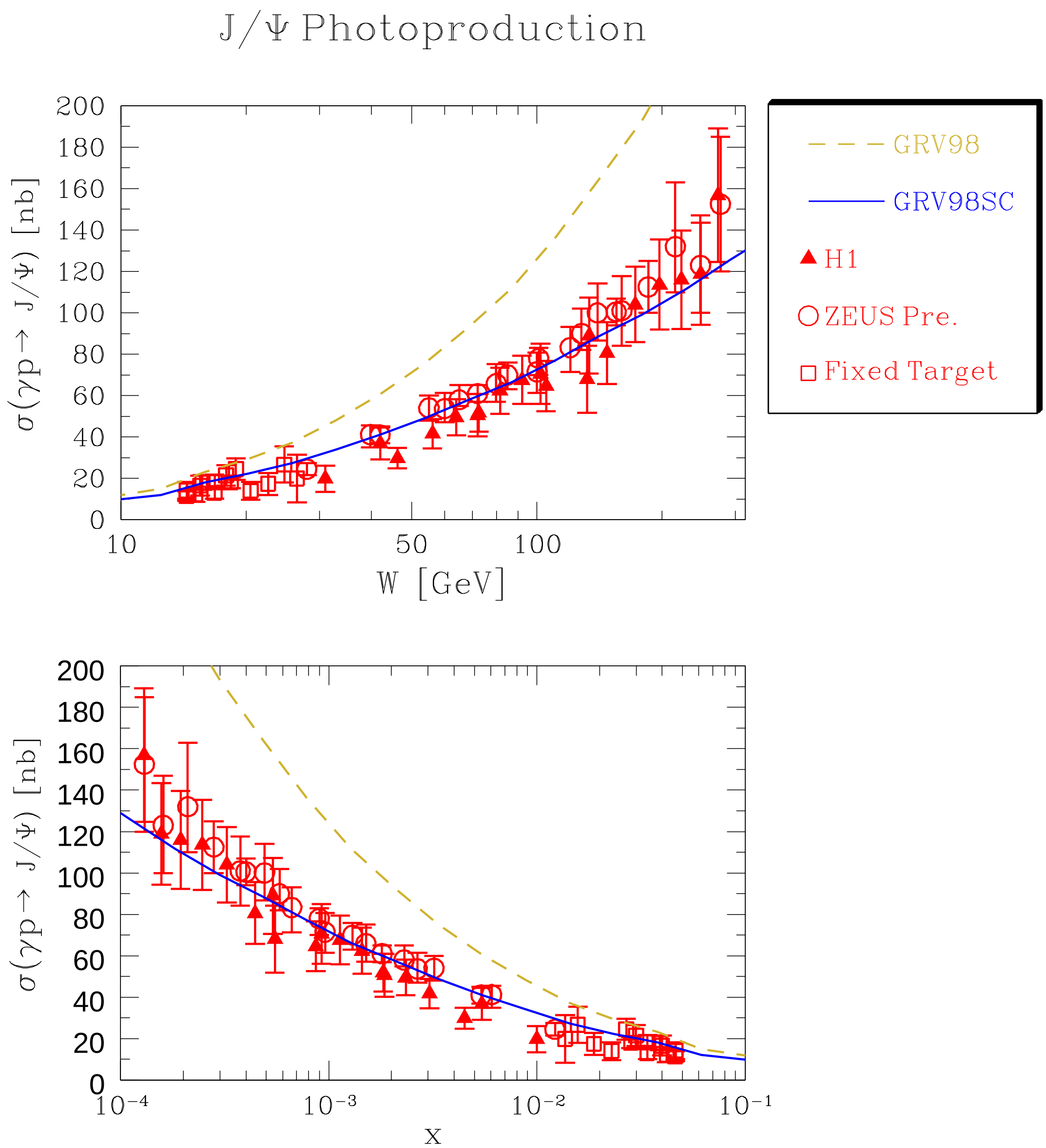

Figure 2: *Photo production of J/Ψ as a function of W and x. Data and GRV98 calculations with and without SC.*

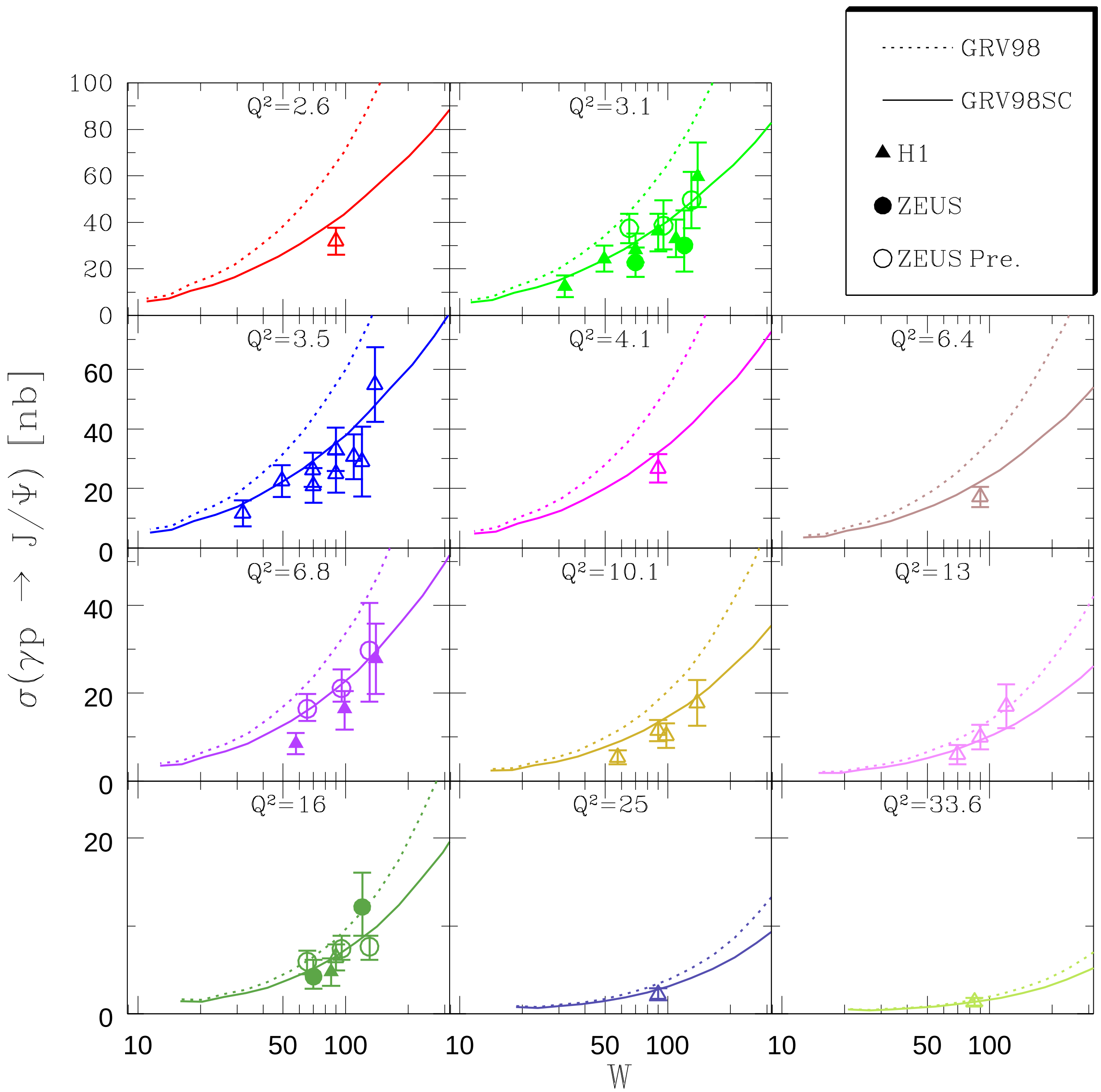

Figure 3: *DIS production of* J/Ψ*. Data and our calculations.*

3) Donnachie and Landshoff (DL) have followed their F_2 analysis[18] with an updated publication on charm production[22] in which they show that the J/Ψ photo and DIS data on the integrated and differential cross sections are compatible with their model, which we denote DL2P. We discuss the differences between DL2P and the predictions of CTEQ5NSC and GRV98SC in the next section.

3 Discussion and Conclusions

The results of the present investigation corroborate the conclusions obtained in our previous study[9] of $\partial F_2/\partial \ln Q^2$, where we have shown that the available data is consistent with either CTEQ5NSC, GRV98SC or DL2P in the kinematic range of $Q^2 \geq 1.9\,GeV^2$ and $x < 10^{-2}$. A comparison of the photo production ($\bar{Q}^2 = 2.4\,GeV^2$) predictions of these models over a wide x range is presented in Fig.5. Following are some concluding remarks

1) The differences between CTEQ5NSC and GRV98SC, within the available experimental kinematic window, are relatively small. We note, though, a systematic difference at low energies ($x > 10^{-2}$) where CTEQ5NSC is considerably larger than GRV98SC. This difference is responsible for the high $\frac{\chi^2}{ndf}$ values we found for CTEQ5NSC. Similar differences also exist for the Q^2 logarithmic slope predictions of these models[9] in the low energy (high x) limit, but relevant data is not available. From the study of J/Ψ photo production we conclude that the GRV98SC parameterization of this process extrapolates well to the very low energy domain in which the soft (npQCD) sector plays an increasingly important role. On the other hand, CTEQ5NSC does not have this property and it overestimates the low energy data.

2) We also note a difference between CTEQ5NSC and GRV98SC in the high energy region ($x < 10^{-4}$). This was not observed in our predictions for the logarithmic F_2 slope and is attributed to our approximate calculation of $D_q^2(J/\Psi)$ which results in a small excess of the SC for very small x. As we noted earlier, an exact calculation of $D_q^2(J/\Psi)$ will improve the results of GRV98SC and bring it close to those of CTEQ5NSC.

3) As we have shown, CTEQ5NSC provides an acceptable reproduction of the high energy photo production data. These results are obtained with $K_F^2 = 1.00$ which implies that the J/Ψ charmonium bound system is strictly non relativistic, or else, that the normalization of the calculation requires some adjustment. We have further investigated this model by applying SC to the calculation with $K_F = 1.00$, denoting it CTEQ5SC. Our output is non satisfactory as it systematically underestimates the data. This result supports our suggestion[9] that CTEQ5 may contain significant screening effects which are absent in the boundary conditions used in GRV98. In this context, it is suggestive to assume that CTEQ5SC results are too small due to a possible double counting of the SC. Our calculated SC introduce a 20% deficiency at $x = 10^{-4}$. We consider this as the uncertainty in the CTEQ5 parameterization in the exceedingly small x limit. This is compatible with the similar conclusion reached in Ref.[9]. The pQCD calculation used in this investigation is performed in the LLA and is, thus, subject to corrections. We distinguish between the normalization of the models we have discussed, which may change, and their hardness as reflected in the energy, or x, dependence, which is a more stable property.

4) Within the available kinematic photo production window, DL2P predictions which differ somewhat from the results of the two pQCD models, still provide an adequate reproduction of the data[22]. At this stage, with the given experimental error bars, one cannot conclusively exclude any of these models. At higher energies DL2P is significantly larger than either CTEQ5NSC or GRV98SC. This feature of DL2P is a consequence of the hard Pomeron component which has a very high Regge trajectory intercept. As a result its energy dependence is

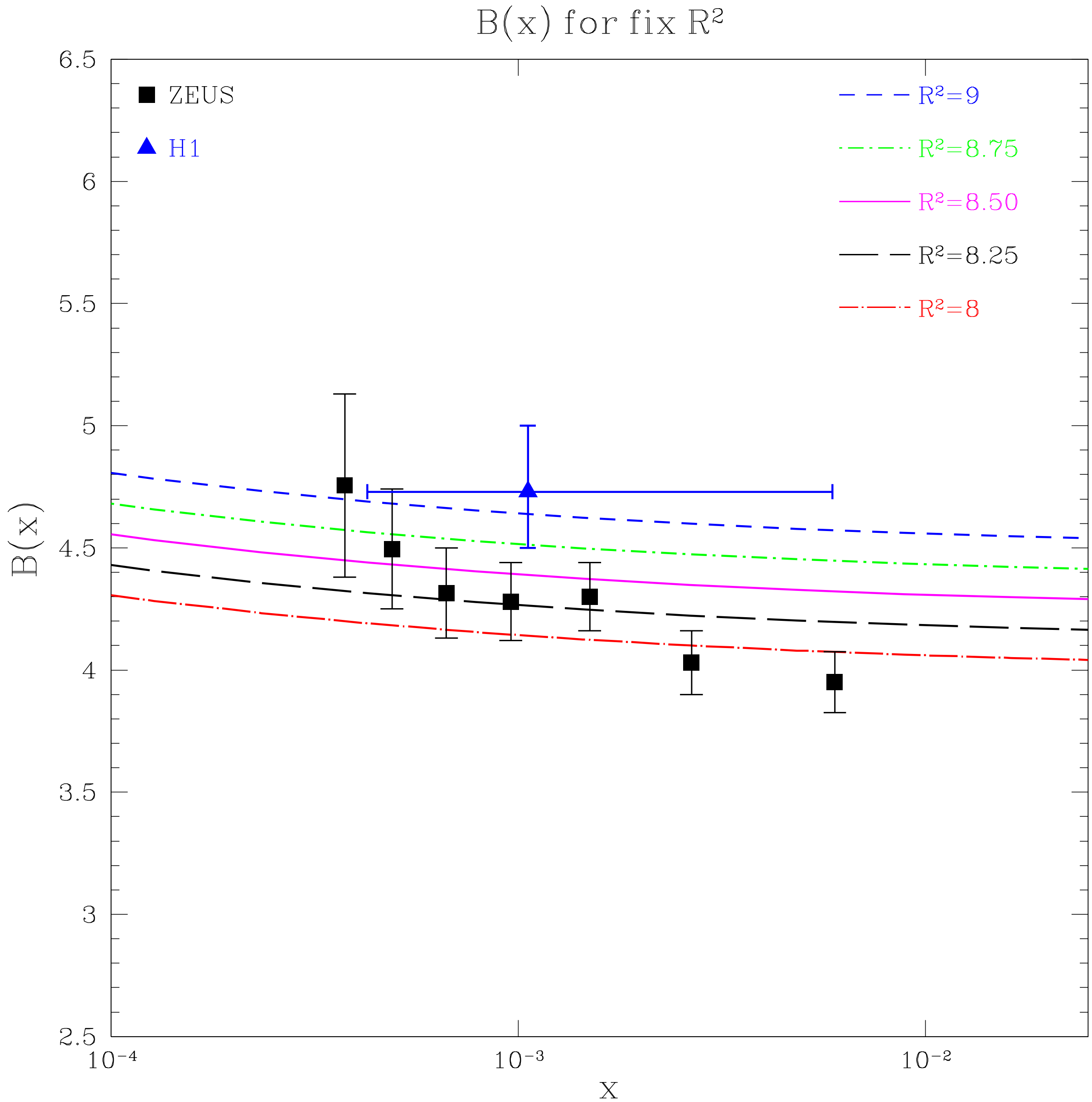

Figure 4: *The energy dependence of the forward differential slope of J/Ψ photo production. Data and SC calculations with several values of R^2.*

much harder than the pQCD models whose λ values are considerably smaller. This is clearly seen at $x = 10^{-5}$ where the DL prediction is about 5 times larger than that of GRV98SC. This x range will become accessible at THERA and, thus, enable an experimental discrimination between DL2P and the pQCD models. The same behaviour of DL2P has also been observed[9] in the small x limit of $\partial F_2/\partial \ln Q^2$.

5) We have investigated the possible role of a soft component, parameterized in the DL form, which was added to GRV98SC. Our analysis shows that such an addition does not improve the $\frac{\chi^2}{ndf}$. We, thus, conclude that any soft component in our model is exceedingly small.

6) The three models discussed have different predictions for B, the J/Ψ forward differential slope. CTEQ5NSC is a model with only a hard, non modified, sector. As such, we expect its B to be a constant for which we took the experimental value. GRV98SC is also a model with only a hard sector but it is corrected by SC. As a result, the model predicts a modest shrinkage of B which is presented together with the data in Fig.4. DL2P is a sum of a soft component, which dominates in the low energy limit and a hard component which dominates in the high energy limit. Since the two Pomerons have different trajectory slopes, DL2P predicts an anti shrinkage effect, where B decreases monotonically with W. The recent ZEUS[12] results contradict this feature.

Overall, our investigation shows that GRV98SC results in a better reproduction of the data than the other two models considered. However, the available data does not enable us, as yet, to conclusively exclude any of the models we have examined.

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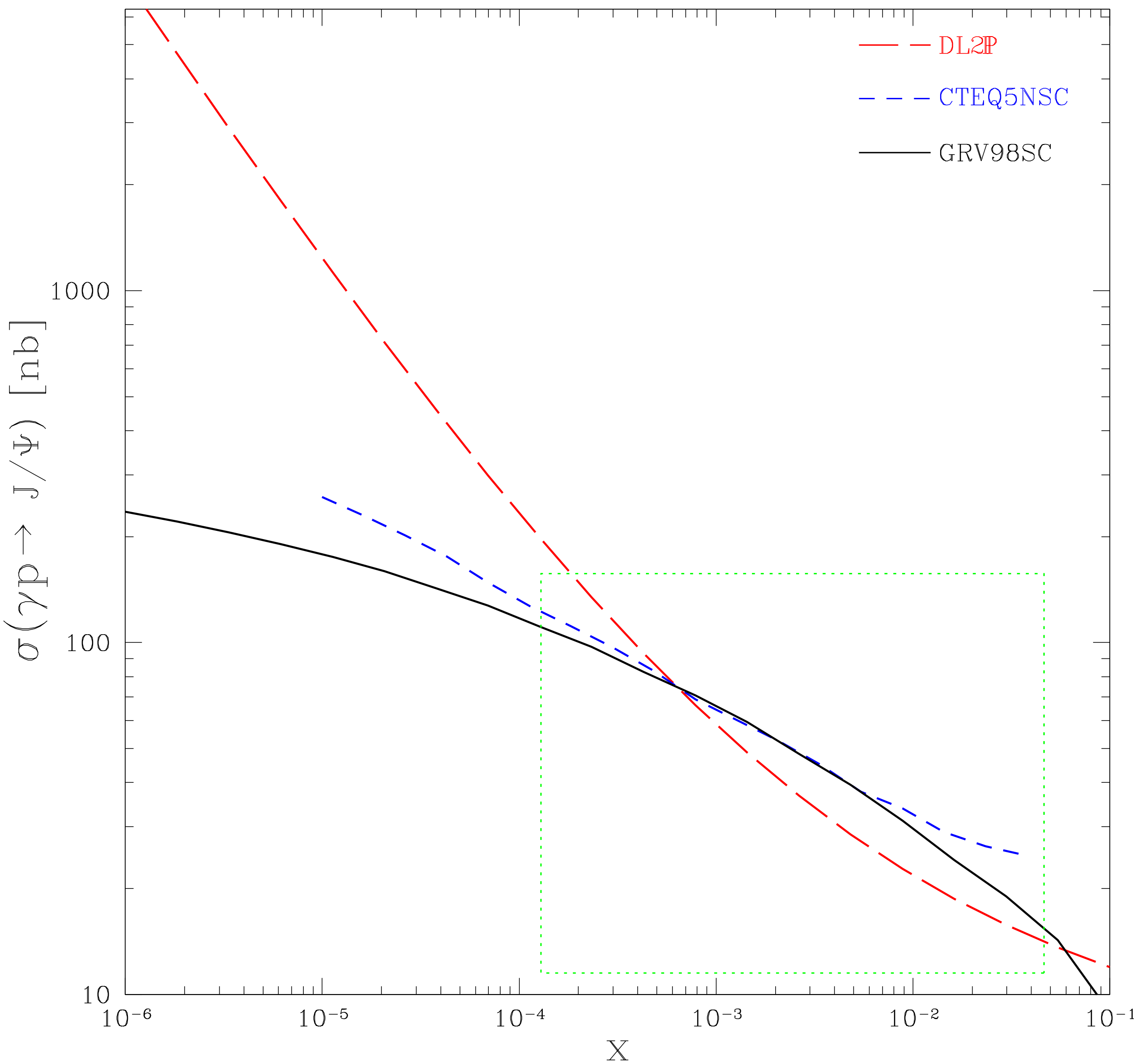

Figure 5: *A comparison between the energy dependence predictions of GRV98SC, CTEQ5NSC and DL2P for the integrated cross section of J/Ψ photo production. The available experimental data points are confined within the inner window.*

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